Contents lists available at ScienceDirect

Journal of Environmental Psychology

journal homepage: www.elsevier.com/locate/jep

Investigating the benefits of viewing nature for components of working memory capacity

Brooke Z. Charbonneau [a,*], Jason M. Watson [b], Keith A. Hutchison [a]

[a] Department of Psychology, Montana State University, USA
[b] Department of Psychology, University of Colorado Denver, USA

ARTICLE INFO

Handling Editor: L. McCunn

Keywords:
Nature
Attention restoration theory
Cognitive processes
Working memory capacity
Attentional control

ABSTRACT

Prior work regarding nature's benefits to different working memory capacity processes is mixed within the existing literature. These mixed results may be due to an emphasis on tasks rather than focusing on construct validity and the underlying mental processes they are intended to measure. When considering underlying process, all might be sensitive to the benefits of nature or perhaps only specific processes of working memory capacity will receive these benefits. Attention Restoration Theory (Kaplan, 1995) would specifically predict that attentional control is the most likely process to benefit from interacting with nature. To address this possibility, three studies investigated whether working memory capacity and its component processes of attentional control, primary memory, and secondary memory benefit from viewing nature images. Montana State University students completed two tasks with a nature or urban image viewed before a block of trials that measured either working memory capacity (Experiment 1), attentional control (Experiment 2), or primary/secondary memory (Experiment 3). Results revealed higher performance after viewing nature images compared to urban images for attentional control but not for working memory capacity or either of its underlying memory components. These results are discussed with respect to the importance of current psychometric standards of measuring behavior when investigating the potential influence of nature on cognition.

1. Introduction

Interacting with natural stimuli has resulted in benefits for a broad range of cognitive domains (Ohly et al., 2016; Stevenson et al., 2018). Nature's benefit for Working Memory Capacity (WMC), the ability to retain and use information in service of a goal without getting distracted, has recently received mixed evidence in the literature (Bratman et al., 2015; Scott et al., 2023). Specifically, despite using the Operation Span task to measure WMC, Bratman et al. (2015) found performance improvements after walking through nature, whereas Scott et al. (2023) did not. Reasons for these differing results could be aspects of the walks, such as the length of the nature walks, characteristics of the natural environments, activities done on the nature walks, and so forth. For example, Bratman et al. (2015) had participants complete a 50-min walk compared to a 30-min walk in Scott et al. (2023). However, the question remains of why WMC might need greater interaction with nature (via longer durations, more beneficial characteristics, or more immersive activities) to receive performance benefits, whereas other cognitive tasks receive benefits from lesser interaction with nature. Another possibility for mixed results could be that specific component processes of WMC benefit while others do not, therefore diluting the benefit of nature and requiring stronger interactions with nature.

The three-component cognitive processes - primary memory, attentional control, and secondary memory - interact to optimize WMC performance (Shipstead et al., 2014; Unsworth et al., 2014), each of which may receive differential benefits from nature. Specifically, primary memory maintains important information relevant to current goals or tasks active in memory. As such, primary memory maintenance is guided by attentional control. Attentional control inhibits distractions and focuses attention on task-relevant information. This relevant information can be active in primary memory, but this information can also be forgotten. If such information is forgotten, secondary memory retrieves stored relevant information not currently active in primary memory. Given the component processes and their interactions, it is important to consider nature's benefits to cognitive abilities, such as WMC, and to deconstruct this tri-partite measure. Therefore, each cognitive ability needs to be tested for the benefits of nature both when combined (WMC) and separately (attentional control, primary memory,

* Corresponding author. 426 Traphagen Hall, Montana State University, Bozeman, MT, 89715, USA.
E-mail address: brooke.charbonneau@student.montana.edu (B.Z. Charbonneau).

https://doi.org/10.1016/j.jenvp.2024.102418
Received 19 April 2024; Received in revised form 29 July 2024; Accepted 3 September 2024
Available online 7 September 2024

and secondary memory) using the same natural stimuli.

Attention Restoration Theory (ART) provides an explanation for nature's potential benefits for cognitive abilities. ART posits that directing our attention is effortful and our ability to do so fatigues over time, but can be restored while in natural environments (Kaplan, 1995; Kaplan & Berman, 2010). Joye and Dewitte (2018) question the notion of fatigue of effortful control and whether attention is truly "restored" while in nature. Although not investigated here, understanding the mixed evidence for the need to fatigue participants (Stevenson et al., 2018) may be assisted by a clearer understanding of what cognitive processes benefit from interacting with nature. For example, if the ability of inhibition is fatigued, this will have little effect on cognition with little overlapping processes, such as working memory (Persson et al., 2007). Therefore, establishing which cognitive processes actually benefit from interacting with nature, and by logical extension, which may well be the most susceptible to the effects of fatigue via manipulation, could help move the ART literature forward.

However, the tasks used to measure the attentional benefits of nature vary widely and are not always in line with the kind of directed attention to which ART refers. More specifically, Kaplan (1995) states that directed attention "... requires effort, plays a central role in achieving focus, is under voluntary control (at least some of the time), is susceptible to fatigue, and controls distraction through the use of inhibition." This definition suggests that not all attention tasks are equivalent or likely to demonstrate performance benefits from interacting with natural stimuli. Indeed, based on the previous theoretical framework of ART, only specific tasks that measure directed attention or processes that recruit directed attention would be likely to receive performance benefits from nature. For the present purposes, it is noteworthy that directed attention, as defined in ART, most closely resembles the cognitive process of attentional control because it involves directing attention toward task-relevant information and away from distractions. Therefore, ART would predict attentional control as the most likely cognitive process to underlie any observed performance benefits after interacting with nature.

To examine which facets of cognition are benefited by nature, Ohly et al. (2016) conducted a systematic meta-analysis focusing on specific tasks. They found nature benefited performance for the Forward Digit Span, Backward Digit Span, and the Trail Making B tests. However, they did not find evidence that interacting with nature improves performance on proofreading tasks, the Necker Cube Pattern Control task, Search and Memory tasks, Sustained Attention to Response Test, Symbol Digit Modalities Test, Symbol Substitution Test, or Trail Making A. Many of the tasks examined within Ohly et al.'s meta-analysis required memory and, more importantly, attention directed towards a goal, but few also incorporated distracting or conflicting information embedded in the task that needs to be inhibited. Thus, the tasks that did not show performance benefits after interacting with natural stimuli may have required less attentional control because distracting information was not integrated into the target stimuli.

The potential, specific benefit of nature for attentional control is perhaps best illustrated by Ohly et al.'s (2016) finding of improved performance for Trail Making B, but not Trail Making A after interacting with natural stimuli. Although participants must connect targets on a paper as fast as possible in both tasks, in version A the targets are only ascending numbers, whereas in version B the targets alternate between ascending numbers and ascending letters. To complete the Trail Making A task, participants need to maintain one set of items, whereas in the Trail Making B task, they need to maintain two sets of items and alternate between them. Thus, participants have to switch back and forth between each set, each time flexibly directing attention towards one set while inhibiting the response required of the other set.

The forward and backward digit span also require flexible disengagement from previously correct responses. The forward digit span is typically considered to be a measure of primary memory whereas the backward digit span can measure attentional control in children, but mostly measures primary memory in adults (St Clair-Thompson, 2010). However, it is important to note that, in both tasks, participants are asked to memorize sequences of letters that they must recall with increasing sets as they progress through the task. With each new set, there is an opportunity for previous sets to interfere with remembering current sets, referred to as a buildup of proactive interference. Therefore, attention control is required to inhibit previously recalled number sets (Engle, 2002). Thus, it is still possible that benefits to attentional control from nature drive improved performance for these digit span tasks. With respect to Ohly et al.'s findings, it is possible that memory processes, as well as some attentional processes, benefit from interacting with nature.

Because no task is process-pure in only measuring the cognitive phenomenon of interest (Jacoby, 1991), Stevenson et al. (2018) updated Ohly et al.'s meta-analysis. They improved upon Ohly et al.'s literature review because, instead of summarizing the evidence regarding nature's influence on cognition by task, they grouped the tasks by their presumed, shared underlying mental processes and considered how these processes might align with several relatively distinct cognitive constructs or domains. Within Stevenson et al.'s framework, for example, *Working Memory* was measured by tasks in which performance relied on manipulation of items actively maintained in primary memory and therefore included different Forward Spans, Backward Spans, and the Reading Span task. Furthermore, tasks reflected *Cognitive Flexibility* if participants had to switch between two sets of rules to complete a task, so the Trail Making B task and the Stroop Switching Task were grouped together. Finally, to capture the construct of *Attentional Control*, tasks were grouped together if performance was based on directing attention toward a target and away from distractions. These tasks included the Necker Cube Pattern Control Task, the executive portion of the ANT, the Stroop task, and the Multi-Source Interference task. Based on their task groupings, Stevenson et al. (2018) found benefits for the cognitive domains of working memory, cognitive flexibility, and attentional control. Several other cognitive domains were examined, but *Visual Attention*, *Vigilance*, *Impulse Control*, and *Processing Speed* showed no reliable effects (Stevenson et al., 2018). They also investigated "emerging" cognitive domains, but they only had one task per domain (hence, there is a lack of confidence in these results compared to the other cognitive domains discussed here). For our purposes, these findings give necessary clues or direction to which cognitive processes benefit from interacting with nature because they focus on the domains or mental constructs that tasks measure, rather than strictly focusing on the tasks themselves.

Although Stevenson et al.'s (2018) grouping of tasks by cognitive domain makes strides to determine which cognitive processes receive benefits from nature, more consideration needs to be given to which underlying cognitive process(es) are reflected in any given set of tasks. For example, there are likely nature benefits to component processes of Stevenson et al.'s domain of *Working Memory*. The working memory tasks in Stevenson et al.'s (2018) meta-analysis were the Reading Span Task, Forward Digit Span, Backward Digit Span, and Forward Spatial Span. However, each of these tasks captures somewhat different cognitive processes. Consider the Reading Span task, which integrates both memory and attentional control and has participants read aloud four-to-six sentences in a row while memorizing the last word of each sentence to recall in order at the end of the set (Daneman & Carpenter, 1980). This task is a measure of Working Memory Capacity (WMC) because primary memory keeps the last words of each sentence active in memory, secondary memory can retrieve these words if they are no longer active, and attentional control keeps focus on the last word and inhibits all other words in the sentence being read aloud. Attentional control ensures that inhibited words are not active in primary memory or accidently encoded in secondary memory. Each of these three component processes works together to influence performance in the Reading Span task. However, the Forward Digit and Spatial Spans are also included in Stevenson et al.'s (2018) meta-analysis as measures of working memory. As stated above, these mainly measure primary memory. Furthermore, the Backward Digit Span measures both primary memory and attentional processing to rearrange the serial order presentation but does not correlate well with complex spans, indicating a lack of measuring secondary memory and attentional control (Hilbert et al., 2015). Because Stevenson et al. (2018) grouped WMC and primary memory tasks together in their meta-analysis, it remains unclear whether WMC or one of its underlying processes was receiving benefits from nature for their *Working Memory* domain.

Stevenson et al. (2018) did independently assess the underlying construct of *Attentional Control*, however, which most closely resembles ART's notion of "directed attention." Therefore, ART would predict attentional control as the most likely process to receive benefits from nature. But, in Stevenson et al.'s (2018) literature review, the ten outcome measures analyzed for attentional control had mixed results. On the one hand, attentional control tasks received benefits from natural stimuli even when participants were not cognitively fatigued before interacting with nature and regardless of whether they were interacting with virtual or real natural stimuli. On the other hand, the benefits of viewing natural stimuli were no longer significant when only examining studies that had equal baseline scores for each condition before interacting with natural or control stimuli (where only 7 out of 17 studies had equal baseline scores). Therefore, it is unclear whether attentional control truly benefits from interacting with natural stimuli.

There are at least two alternative explanations for weaker nature-based benefits for attentional control tasks. First, traditional attentional control measures do not typically correlate well with one another resulting in poor psychometric properties. Often, researchers use accuracy or reaction time difference scores as the dependent measure in attentional control tasks like Stroop and Flanker. Difference scores based on reaction time ignore accuracy and vice versa. In addition, difference scores are notoriously low in reliability when derived from measures that are correlated with one another. Therefore, using only accuracy or reaction times does not account for speed-accuracy tradeoffs (see footnote 4; Draheim et al., 2021). As a result, Draheim et al. (2021) recommend avoiding these problems and improving attentional control measures by using tasks that are accuracy-only or deadline measures, instead of relying on differences in reaction times and accuracy as dependent measures for these tasks. When using accuracy-only tasks or imposing deadlines that are adjusted based on accuracy to equate speed-accuracy tradeoffs, these tasks correlated highly with one another and are highly related to latent factors of attentional control. Thus, it is possible that the traditional tasks included in Stevenson et al.'s (2018) meta-analysis may not have adequately captured attentional control processes (particularly if these tasks were not deadline or accuracy-based measures, per the recommendations of Draheim et al., 2021). Specifically, the executive portion of the Attention Network Task (ANT) score, which is just a Flanker task, and the Stroop were used for nine out of 17 studies. Additionally, eleven of the studies used difference scores or only considered accuracy or reaction time and ignored the other. In this light, the mixed results for their *Attentional Control* construct could have been due to the fact that one or more of the dependent measures included in their meta-analysis did not reflect current psychometric perspectives on the most optimal way to measure the underlying process of attentional control.

Second, it is possible that the benefits nature provides affect memory in addition to, or instead of, attentional control. The two meta-analyses discussed above showed nature benefits are present for primary memory tasks such as the forward digit span (Ohly et al., 2016) and for the *Working Memory* construct (Stevenson et al., 2018). Performance gains after interacting with natural stimuli in memory tasks could be due to nature benefiting the memory processes themselves or through benefiting attentional processes that are also captured by memory task measures. For example, both memory encoding and retrieval require the voluntary focusing of attention (Fernandes et al., 2005; Schacter, 1996).

1.1. Underlying processes and selection of cognitive tasks

Careful selection of cognitive tasks is vitally important because tasks that include additional cognitive processes other than those of interest could diminish the measured benefit of interacting with nature. Therefore, in our experiments, two tasks for each construct were used to measure WMC, primary memory, secondary memory, and attentional control. These tasks have previously been shown to strongly reflect these cognitive processes of interest. Using multiple tasks per construct helps minimize measurement error caused by task-specific abilities and, therefore, increases confidence that nature benefits the underlying construct of interest. Our selection of tasks was, therefore, based on which tasks are highly related to their respective constructs at the latent level (Draheim et al., 2021; Shipstead et al., 2014).

Because these data were collected from 2020 to 2022, COVID-19 restrictions limited the types of tasks we could use in our study while our in-person lab was closed and participant testing shifted online. Although the Operation Span and Symmetry Span best measure WMC in Shipstead et al. (2014), the Operation Span had to be replaced. WMC tasks can only be effectively administered online without participants cheating if researchers avoid using to-be-remembered stimuli that would be easy to write down, such as numbers or letters (Hicks et al., 2016). Therefore, the Operation Span, which has participants memorize letters, was replaced with the Rotation Span, which has participants memorize arrows, which is still highly related to WMC (Draheim et al., 2021). This same logic was also applied to primary and secondary memory tasks, in which numbers and letters were replaced with images and Klingon symbols (Hicks et al., 2016). In addition, in Shipstead et al. (2014), only the Antisaccade was highly related to attentional control because the traditional Flanker and Stroop tasks relied on reaction time difference scores. Therefore, the Flanker was replaced with a deadline Flanker that adjusts the response deadline for an equalized accuracy between participants and used this adjusted deadline for the dependent measure (Draheim et al., 2021). Careful selection of these measures based on previous literature testing their construct validity allows more confidence in which cognitive processes might receive benefits from interacting with natural environments.

1.2. Current study

In the current study, we used three experiments in which three different, *specific* cognitive processes could theoretically benefit from interacting with nature. To determine which cognitive process (or processes) benefits from interacting with nature, participants completed either two WMC tasks (Experiment 1), two attentional control tasks (Experiment 2), or three tasks that measured primary and/or secondary memory (Experiment 3) with images of natural and urban settings integrated into the tasks to examine performance on trials following nature images versus trials following urban images. In line with Platt's (1964) recommendation of objectively pitting multiple hypotheses against one-another, our competing hypotheses are our *sensitivity* hypothesis and our *specificity* hypothesis.

Our *sensitivity hypothesis* predicts that WMC would be the most likely to have benefits to performance due to it being a composite measure in which one or more of its three underlying cognitive processes could be receptive to nature manipulations (i.e., a "more is more" prediction) when keeping nature exposure the same. A recent replication and meta-analysis concluded that using images of nature produce unreliable effects for benefits to directed attention (Johnson et al., 2021). Perhaps this is due to subtle benefits of nature when the interaction is minimally immersive. Given the likely subtle effects of images, WMC may be the most likely to receive benefits from viewing nature images because multiple processes may receive small benefits that could accumulate into a larger overall benefit. If each component process itself – primary memory, secondary memory, and attentional control – is sensitive to benefits from interacting with nature, the WMC tasks (Experiment 1) that capture all of the components should be the most receptive to our nature manipulation. Therefore, according to a *sensitivity hypothesis* WMC tasks will be the only tasks to receive benefits from viewing nature images compared to urban images (or will receive the largest benefit).

In contrast, our *specificity hypothesis* predicts the opposite in that only particular components of WMC would receive benefits to performance after interacting with nature, such as attentional control from the perspective of ART (i.e., a "more is less" prediction). It is possible that the lesser immersion of nature by using images only affects one or two processes. In this case, WMC would have a diluted (and possibly no) benefit in Experiment 1, with effects of nature on performance instead being observed in either Experiment 2 (attentional control) or Experiment 3 (primary and/or secondary memory). Consistent with this idea, Stevenson et al. (2018) found evidence for nature's beneficial effect on attentional control. Yet, there was less reliable evidence of benefits for attentional control tasks than the primary memory and WMC tasks that were categorized together under the *Working Memory* construct. Therefore, there is also a possibility that primary memory, secondary memory, or both may receive the greatest effects from nature, and it is possible that previous attentional task performance gains were truly measuring memory benefits, such as remembering the goal of the task, which is important for performance on attentional control tasks (Hood & Hutchison, 2021). Taken together, these three experiments allow testing for the impact of nature on all three components of WMC both when combined (Experiment 1) and when tested separately (Experiment 2 & Experiment 3), adjudicating between a *sensitivity* and a *specificity hypothesis* to determine which cognitive processes receive benefits from nature.

2. Experiment 1

Experiment 1 examined a potential benefit of nature on WMC performance by comparing the recall of sets of items in the Rotation and Symmetry span WMC tasks after viewing nature or urban images. The complex span tasks are designed to measure individual differences in WMC, but WMC performance is subject to state-based effects such as emotional state, cognitive load, arousal, mood, etc. (Ilkowska & Engle, 2010). For instance, emotional processing competes with cognitive processing, which could lead to diminishing working memory ability (Ilkowska & Engle, 2010). If participants increase the number of completely recalled item sets after viewing nature images, compared to urban images, then this would be evidence that WMC benefits from interacting with nature, therefore providing evidence for our *sensitivity hypothesis*. A null effect would provide evidence for our *specificity hypothesis* and lead to an investigation of which particular underlying cognitive process (or processes) might benefit from interacting with nature per Experiment 2 and 3. Analyses were conducted in R Statistical Software (v4.3.1; R Core Team, 2023). Additionally, to evaluate the evidence for the alternative and null hypotheses, we also conducted Bayesian analyses in JASP Version .18.3 (JASP Team, 2024). IRB approval was obtained through Montana State University for all three experiments [IRB Exempt Protocol #BC020121-EX].

2.1. Materials and methods

2.1. 1. Participants

Using G*Power, 74 participants were required to reach 80% power, given an average effect size ($\eta_p^2 = .0195$) for a repeated measures *t*-test examining the effect of viewing natural compared to urban images for a change localization task used for measuring WMC (González-Espinar et al., 2023). Therefore, we decided to test at least 80 participants in each experiment. Eighty-five participants between the ages of 18–48 were recruited from the Montana State University Subject Pool for credit in an introductory psychology course or extra credit in higher-level psychology courses. Attention checks were used to ensure participants were engaged within each set of tasks. These attention checks were a series of three questions presented toward the beginning and end of the task that asked a given question in slightly different ways (Maniaci & Rogge, 2014). For example, on a 5-point scale, participants rated the degree to which they agreed with the statement "In general ... I am a very energetic person" toward the beginning of the procedure and "In general ... I have a lot of energy" toward the end of the procedure. Given these questions' similarity, a participant's answers should be the same if properly engaged for the three question pairs. That is, if a person rated the former statement as a 5 (highly agree), they should rate the latter statement with a similar number, such as a 4 (agree) or 5 (highly agree). Therefore, our attention check measure took the sum of the absolute difference between each of the three pairs to determine the discrepancy of their answers towards the beginning and the end of the procedure. A total of seven or more points of deviation were considered a failure to pay attention, and therefore, participants who received seven or more points were not included in the analysis. These types of attention checks are effective at identifying extreme inattentiveness and are more subtle attention checks than instructional attention checks (Maniaci & Rogge, 2014). Three participants who completed the WMC tasks failed the attention checks and were removed from further analysis, resulting in 82 participants' data being included in the final analysis (M age = 19.57, SD age = 3.69, 37 male, 39 female, one other, and five invalid responses). Results remained the same with and without exclusion criteria for all experiments. Five participants could not complete parts of the demographics portion of the experiments because the questions did not appear on the screen. This was only reported during the demographics portion of the experiment and only for some participants. This is a known bug of the E-Prime 3 software (Psychology Software Tools, 2022).

2.1. 2. Procedure

Participants signed up for the experiment through the Montana State Subject Pool SONA systems and then were given a Qualtrics survey that provided them with a consent form (Qualtrics, 2005). After they agreed to participate, they received a download link for the WMC tasks programmed in E-Prime 3 (Psychology Software Tools, 2016) and distributed with E-Prime Go (Psychology Software Tools, 2020). In total, there were 40 natural images and 40 urban images used in this procedure, which can be found in Appendix A. Each task was modified to present one of 20 urban images (Berman et al., 2008)[1] or 20 high-fascination nature images (Szolosi et al., 2014) for 10 s before each block of trials of the Symmetry Span and Rotation Span. The order of the two tasks was randomly presented for each participant. At the end of the study, demographic information and preference for nature over urban settings were collected.

2.1. 3. Nature and urban images

To create a more robust virtual manipulation for natural versus urban environments, the experiment used environmental images that have successfully produced benefits for cognitive tasks. ART has four components through which nature presumably restores attention: fascination, extent, compatibility, and being away (Kaplan, 1995). Fascination is involuntary interest in the natural environment, and manipulations of high and low-fascination images have previously been shown to affect cognition (Hartig et al., 1996). Additionally, extent is the degree of immersion that participants experience the natural stimuli, which may be important for fascination's ability to affect cognition (Kaplan, 1995). To test the effects of manipulating fascination in natural images, Szolosi et al. (2014) had participants complete a Recognition Memory Task for images high and low in terms of mystery and

[1] Berman et al. (2008) had 50 urban images, but Szolosi et al. (2014) only had 40 highly fascinating nature images. Therefore, ten of the 50 urban images were not used for these experiments. These ten urban images were selected for removal if they had some natural features in the image or contained blurriness.

fascination. Both mystery and fascination related to recognition performance; however, fascination ratings fully mediated mystery's positive effect on recognition performance, indicating that greater fascination led to greater recognition of these images when viewing them for 1, 5, or 10 s, but not 300 ms. These results suggest that viewing these highly fascinating images for 10 s provides an adequate interaction with nature to receive cognitive benefits.

For the urban images, Berman et al. (2008) had participants complete the Backward Digit Span and the Attention Network Test before and after viewing a block of natural or urban images. Although performance improved after viewing nature images for these two tasks, increasing backward digit span and benefiting the executive portion of the ANT, notably, the urban images did not significantly affect performance on the Backward Digit Span or any measures included in the Attention Network Task, indicating that these images are not likely to influence performance on cognitive measures. Therefore, Berman's urban images were used for our three experiments to act as a control setting to go along with the set of highly fascinating nature images described above. An example of the nature and urban images used in this study can be seen in Fig. 1. Moreover, returning to Appendix A, as expected, additional norming data we collected on these image sets revealed urban scenes were indeed rated as significantly less fascinating than the nature ones. Furthermore, in addition to separating on fascination, these nature and urban images were rated differently on other dimensions including likability and mindfulness, which may influence behavioral performance, a point to which we will briefly return in the General Discussion.

2.1. 4. Working memory capacity complex span tasks

For the WMC complex span tasks, participants were first presented with a nature or urban image for 10 s and were then asked to memorize items one-at-a-time between logical judgments. The sequences of items could be 2-to-5 items long for each set of to-be-remembered stimuli. Items in these sets could be repeated between the sets of to-be-remembered items but never within the same set on a given trial. Finally, participants were asked to recall the items they memorized in the order they were presented. Each span task had 40 sets total that were presented in a random order, with 20 sets following nature images and 20 sets following urban images (with five nature and five urban image trials at each of the different length set sizes 2–5 as described above). The dependent measure for both tasks was the sum of completely correct recall of a given set of items to-be-remembered, typically referred to as the Absolute Score in a complex span task, resulting in a range from 0 to 70 for possible scores on each complex span task for each image type.

2.1. 4.1. Symmetry Span. For this complex span, participants viewed an image for 10 s and then were asked whether two different matrices were symmetrical for their logical judgment (Foster et al., 2015). Specifically, they had to determine whether cells filled in on an 8 × 8 matrix were symmetrical along the vertical axis. After each symmetry judgment, participants were asked to memorize the locations of highlighted cells within a 4 × 4 matrix. This sequence continued 2-to-5 times before they were asked to recall all to-be-remembered cells that were highlighted in the correct order. The progression of this task can be seen in Fig. 2A.

2.1. 4.2. Rotation Span. After seeing an image for 10 s, participants were asked if a letter was facing the correct way after it had been rotated

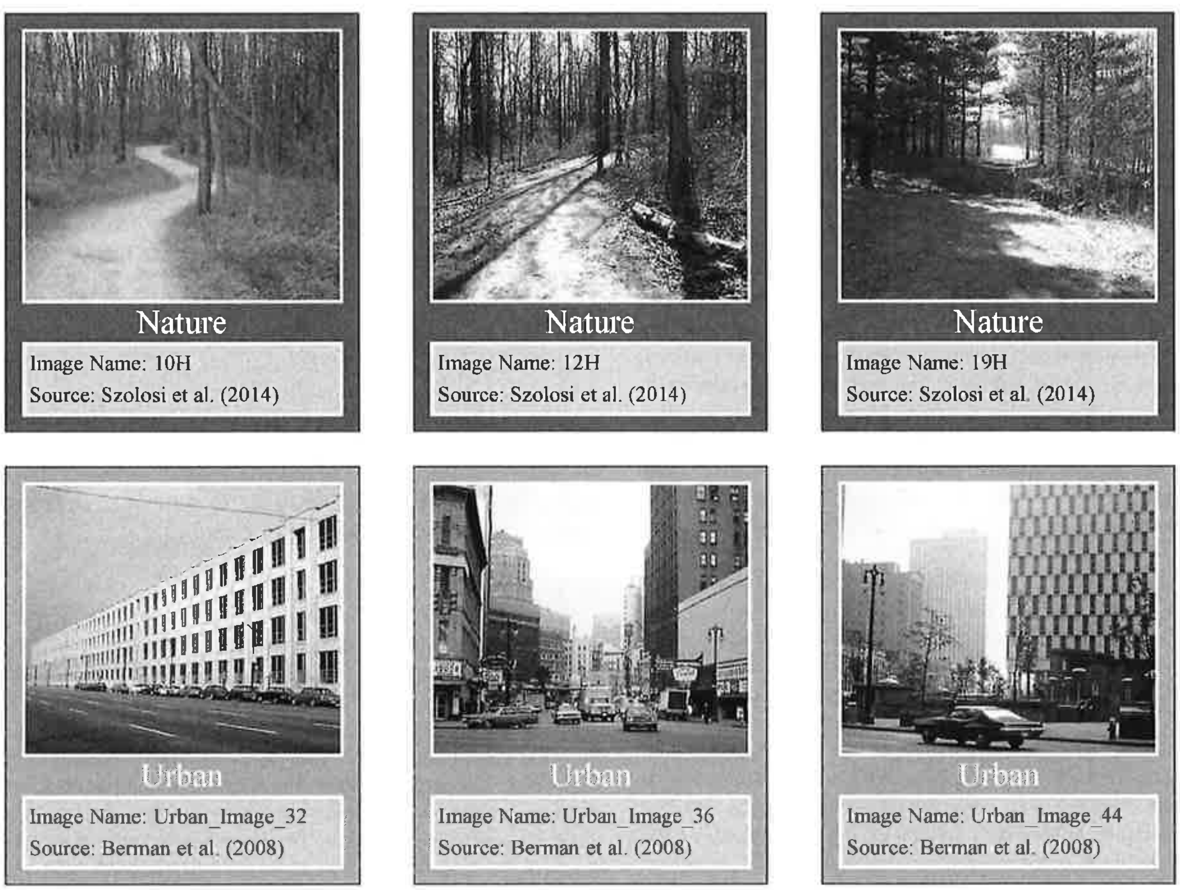

Fig. 1. Example nature and urban images.
Note. The Image Name refers to the name of the images presented in the norming means table on OSF (https://osf.io/p2rzc/?view_only=b31fb7e310fa4214af640f9d13bb0c1d).

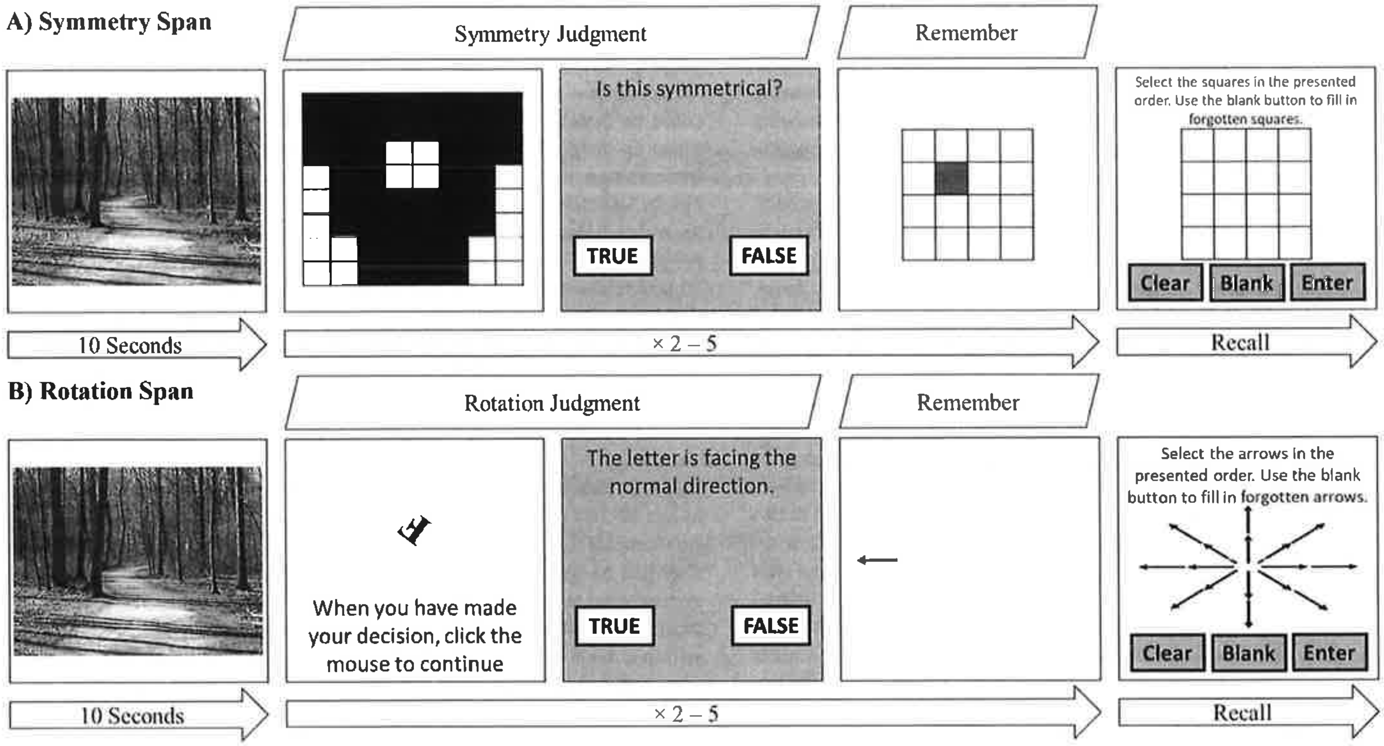

Fig. 2. Diagrams of nature and urban images presented before complex span sets.
Note. An image with a natural setting is shown in the figure. In the actual task, a nature or urban image was shown for 10 s prior to each set of stimuli.

(Foster et al., 2015). Participants were then asked to memorize the location and direction of an arrow. This sequence continued 2-to-5 times before they were asked to recall all to-be-remembered arrows that were highlighted in the correct order. The progression of this task can be seen in Fig. 2B.

2.2. *Results and discussion*

Performance, as reflected by the absolute score for each complex span task following nature or urban pictures, was standardized to allow a combined analysis across tasks. Descriptive statistics prior to *z*-score transformation are reported in Table 1. After the transformation, the data was checked for outliers and normality. There were no observations that were 1.5 standard deviations below the first quartile or above the third quartile of the *z*-scores using the psych package (v2.4.1; Revelle, 2024). The data was also determined to be normally distributed using QQ plots using the ggpubr package (v0.6.0; Kassambara, 2023). With the *z*-transformed scores, a Task by Image Type (nature vs. urban) ANOVA was conducted to analyze the effect of viewing these images on the recall of item sets using the rstatix package (v0.7.2; Kassambara, 2023). We compared the model containing the effects from our two-way repeated measures ANOVA to a null model missing each effect. The resulting Bayes factor (BF_{10}) reflects the better fit when a main effect or interaction is added to the model compared to when it is absent. Therefore, a BF_{10} below 1 would indicate that the null is a better fitting model, whereas above 1 indicates that the effects improve the model. According to the classification scheme from Lee and Wagenmakers (2013; adjusted from Jeffreys, 1961), a BF_{10} of 10–30 = strong evidence, 3–10 = moderate evidence, 1–3 = anecdotal (weak) evidence, and 1 = no evidence. Therefore, values less <1 equal evidence for the null, such that .33 would be moderate evidence for the null and .10 would be strong evidence for the null model. There was no main effect of Image Type [$F(1,81) = .016$, $p = .899$, $\eta_p^2 < .001$, $BF_{10} = .147$] and no Task by Image Type interaction [$F(1,81) = .264$, $p = .609$, $\eta_p^2 = .003$, $BF_{10} = .200$], indicating that there was no difference in performance after viewing nature images compared to urban images, indicating an equal null effect across our two tasks. Results did not change when using partial scoring rather than absolute scoring for the complex spans.

We also conducted an exploratory analysis to examine if the size of the set may have influenced the size of the nature effect. When adding set size to our model, there was no main effect of Image [$F(1,81) < .001$, $p = 1.000$, $\eta_p^2 < .001$], nor an interaction between Image and Set Size [$F(3,243) = .425$, $p = .735$, $\eta_p^2 = 005$]. Therefore, the null effect was most likely not due to the difference in difficulty from one set size to another.

Our results indicated that viewing natural settings does not benefit WMC, with moderate to strong evidence for a null effect, therefore providing evidence inconsistent with our *sensitivity hypothesis*. Because WMC did not receive any benefits from interacting with nature, it is possible that some underlying components of WMC receive benefits and others do not, therefore diluting the potential benefits to WMC. To address this possibility, we next test the *specificity hypothesis* in Experiments 2 and 3 by examining and isolating cognitive processes that contribute to WMC (i.e., attentional control, primary memory, and secondary memory) and whether one or more of these processes may receive benefits from interacting with nature.

3. Experiment 2

Experiment 2 examined the difference in attentional control performance for the Antisaccade and Flanker Deadline tasks after viewing nature or urban images. If performance improves for these tasks after viewing nature images rather than urban images, this would be evidence that the attentional control component of WMC receives benefits, and any WMC benefits are likely diminished by components that do not receive benefits (e.g., primary and/or secondary memory), consistent with our *specificity hypothesis*. The same power criteria were used from Experiment 1, indicating that at least 74 participants were required to reach 80% power.

Table 1
Unstandardized descriptive statistics for raw scores of working memory capacity tasks.

Task	Cronbach's α	Image Type	N	Mean (*SD*)	95% CI	Standard Error	Min	Max	Skew	Kurtosis
Symmetry Span	.902	***Nature***	82	40.12 (16.08)	±3.533	1.776	0	70	−.272	−.790
		Urban	82	40.35 (15.92)	±3.497	1.758	0	67	−.356	−.534
Rotation Span	.912	***Nature***	82	37.10 (15.64)	±3.437	1.727	0	70	−.184	−.704
		Urban	82	36.70 (15.28)	±3.65	1.687	4	70	−.224	−.515

Note. The scores of the Symmetry Span and Rotation Span were significantly and positively correlated ($r = .67, p < .001$). CI = 95% Confidence Interval.

3.1. Materials and methods

3.1. 1. Participants

Ninety participants between the ages of 18–44 were recruited from the Montana State University Subject Pool for credit in an introductory psychology course or extra credit in higher-level psychology courses. Two participants failed the attention checks that were described in greater detail above, and these participants were excluded from the analysis of the final data set (N = 88, M age = 20.29, SD age = 3.92, 38 male, 43 female, and seven invalid responses).

3.1. 2. Procedure

The procedure was the same as Experiment 1, but participants completed two attentional control tasks in a random order rather than two WMC tasks.

3.1. 3. Nature and urban images

The same images were used as in Experiment 1.

3.1. 4. Attentional control tasks

3.1. 4.1. Antisaccade. Participants saw a nature or urban image every eight trials for 10 s each. Within each trial, a participant first saw a fixation sign in the middle of the screen for 1–2 s. Next, a saccade cue "*" was presented on one side of the screen for 300 ms. Participants were told that they should look on the other side of the screen immediately to catch a target letter when this cue appeared. On the opposite side of the asterisk, the target letter O or Q was presented for 100 ms and immediately replaced by a pattern mask (##) where participants had to respond whether they saw an O or a Q. Participants had to respond within 5 s of the mask presentation. The sequence of seeing an image followed by eight Antisaccade trials was completed 40 times for 20 nature images and 20 urban images in a randomly presented order. This task is depicted in Fig. 3A. The accuracy of letter identification was the dependent measure (Hutchison, 2007).[2]

3.1. 4.2. Flanker Deadline. Participants saw either a nature or urban image every 18 trials. Each trial started with a 450–900 ms fixation point "+" and then five arrows presented on the screen. The flanking arrows were either facing the same direction (congruent condition, →→→→→) or the opposite direction (incongruent condition, →→←→→) from the middle arrow. Each set of 18 trials was 67% congruent. The response deadline for the first block of 18 trials was 1050 ms. If the participant was accurate for at least 15 of the 18 trials, the response time decreased by 90 ms. Otherwise, it increased by 270 ms for the next block (Draheim et al., 2021). Participants were asked to indicate the direction the middle arrow was facing as quickly as possible by pressing the left arrow key (Z) or the right arrow key (/). The sequence of seeing an image followed by eighteen Flanker trials was completed 40 times for 20 nature images and 20 urban images in a randomly presented order. This task is depicted in Fig. 3B.

Due to the image type being manipulated and randomly ordered within the task, the final deadline was influenced by both image types. Although the typical dependent variable is the final deadline at the end of the task, this would have been influenced by both nature and urban images due to the within subjects manipulation of image type. Therefore, the dependent variable was calculated by giving a point to a participant's score every time the deadline decreased (they were accurate for 15 or more trials) and subtracting a point from their score every time their deadline increased (they were accurate for 14 or fewer trials) and this score was calculated separately for blocks of trials following nature images and blocks following urban images. Therefore, because they saw 20 of each type of image, their final score ranged from −20 to 20 for both nature and urban trials, such that a negative score between 0 and -20 indicates an average increase (or slowing down) in the deadline following that image type and a positive score between 0 and 20 indicates an average decrease (or speeding up) in the deadline following that image type. Using deadlines in this manner provides a way to prevent participants from artificially inflating their accuracy by having longer reaction times (Draheim et al., 2021).

3.2. Results and discussion

Z-scores for the Antisaccade and for the Flanker Deadline were computed within each task to compare the potential benefit of nature across tasks. Descriptive statistics from the unstandardized scores are reported in Table 2, in which the dependent variable for the Antisaccade is the overall accuracy for each of the trial types and for the Flanker Deadline was the sum of each time the person's deadline sped up (+1) or slowed down (−1). The positive mean obtained for both Nature ($M = 7.625$) and Urban ($M = 6.226$) Image types indicates that participants generally sped up over the course of the experiment. The greater mean for the nature image type trials indicates that participants decreased/ shortened their deadlines more often after viewing nature images. From both tasks, ten observations were identified as outliers within the data that resulted in a violation of normality. However, the results did not change whether the outliers were or were not included in the data, so all observations were kept for all following analyses. With all *z*-transformed scores, a Task by Image Type (nature vs. urban) ANOVA was conducted to analyze the effect of viewing these images on performance for the Antisaccade and Flanker Deadline tasks. For the attentional control tasks, there was a main effect of Image Type [$F(1,87) = 8.832, p = .004, \eta_p^2 = .092, BF_{10} = 3.031$] such that performance on nature trials was .108 standard deviations greater than performance on urban trials. However, there was also a Task x Image Type interaction [$F(1,87) = 5.683, p = .019, \eta_p^2 = .061, BF_{10} = 3.789$], indicating that the effect of nature significantly differed between the two tasks. To decompose this interaction, performance for nature and urban trials was compared for both tasks using paired samples *t*-tests. Performance did not differ between nature and urban trials for the Antisaccade, $t(87) = .648, p = .518, BF_{10} = .144$, CI 95% [-.048, .094], but did for the Flanker Deadline task, $t(87) = 2.790, p = .006, BF_{10} = 4.392$, CI 95% [.093, .552], such that performance was .322 standard deviations greater on nature trials

[2] Although we are not measuring eye movements directly, past studies have demonstrated the validity of this method in accurately capturing eye movement behavior (see Hood et al., 2022, footnote 2).

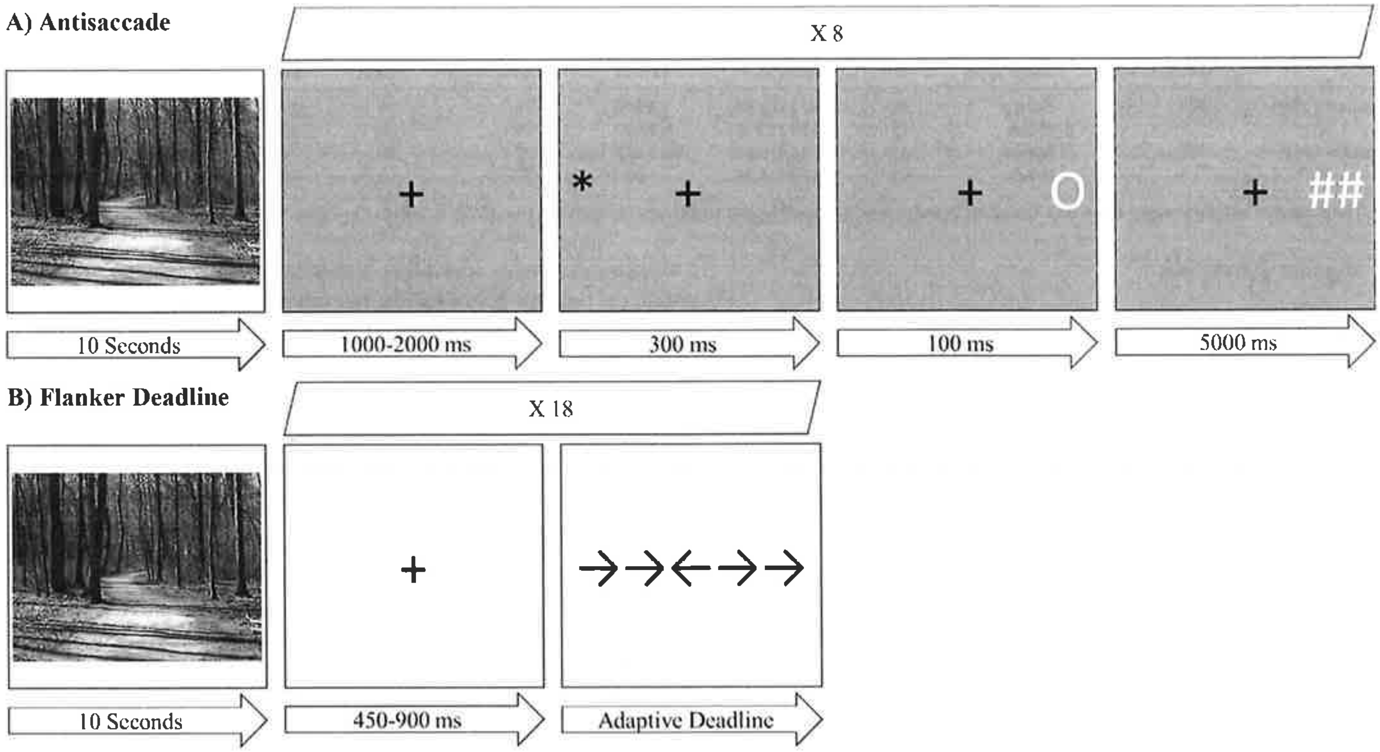

Fig. 3. Diagrams of nature and urban images presented before attentional control tasks.
Note. Although an image with a natural setting is shown in the figure, a nature or urban image was shown for 10 s.

Table 2
Unstandardized descriptive statistics for raw scores of attentional control tasks.

Task	Cronbach's α	Image Type	N	Mean (*SD*)	95% CI	Standard Error	Min	Max	Skew	Kurtosis
Antisaccade	.976	***Nature***	88	.774 (.155)	±.033	.017	.319	1.00	−.937	−.006
		Urban	88	.770 (.158)	±.033	.017	.175	.994	−1.068	.912
Flanker Deadline	.803	***Nature***	88	7.625 (4.249)	±.900	.453	−11	15	−3.228	12.261
		Urban	88	6.216 (4.401)	±.932	.469	−16	12	−3.740	16.238

Note. The scores of the Antisaccade and Flanker Deadline tasks were significantly and positively correlated ($r = .52, p < .001$). CI = 95% Confidence Interval.

compared to urban trials.[3] Overall, these results provide preliminary evidence that nature specifically benefits attentional control.

However, benefits were only significant for one control task but not the other. An exploratory analysis was conducted to see if screen size could capture error variance because the Antisaccade could be easier with a smaller screen in which the participant can monitor both sides of the screen at once. The screen size was determined by the Monitor ID from diagnostic information that was collected with E-Prime Go. The exploratory analysis confirmed that when controlling for screen size in a 2 (Task) x 2 (Image Type) ANCOVA, there was indeed a main effect of Image Type [F (1, 84) = 3.970, p = .0496 ηp2 = .045] and no Task × Image interaction [F (1, 84) = 1.504, p = .224, ηp2 = .018]. Although, interestingly, those with smaller screens (M = 74.7%) performed worse than those with larger screens (M = 82.1%). This is a point to which we will return to later in the General Discussion.

Given that viewing nature images for 10 s before a set of trials improved performance compared to viewing urban images, nature appears to benefit attentional control, in particular. This provides evidence consistent with our *specificity hypothesis*, which predicts that interacting with nature may benefit individual components of WMC, such as attentional control, but not necessarily all three of its components. However, it is still possible that primary and/or secondary memory processes will benefit from interacting with nature as well; therefore, in Experiment 3, we focus on these two remaining, underlying components of WMC.

4. Experiment 3

Experiment 3 examined the memory components of WMC to determine if viewing natural compared to urban stimuli increased performance for either primary or secondary memory. The two primary memory and secondary memory tasks were based on the tasks used by Shipstead et al. (2014) that loaded highest onto primary memory and secondary memory in their confirmatory factor analysis. In their study, participants performed a digit span that loaded onto primary memory and a continuous paired associates task that loaded onto secondary memory. In addition, they performed a recall task in which items recalled within either seven presented or remembered items were counted as primary memory, and the remaining recalled items were counted as secondary memory. These tasks contain letters and numbers, so they were modified in our experiment to present icons and symbols to prevent possible cheating (Hicks et al., 2016). Some symbols used were 'Klingon' letters and numbers from a language featured in the television show Star Trek. An example of these letters and numbers can be seen in

[3] These same results were obtained when using accuracy as the dependent measure for the Flanker task, rather than deadline. Specifically, there was a main effect of Image Type [$F(1,87) = 8.836, p = .004, \eta_p^2 = .092$] and an Image Type × Task interaction [$F(1,87) = 4.754, p = .032, \eta_p^2 = .052$].

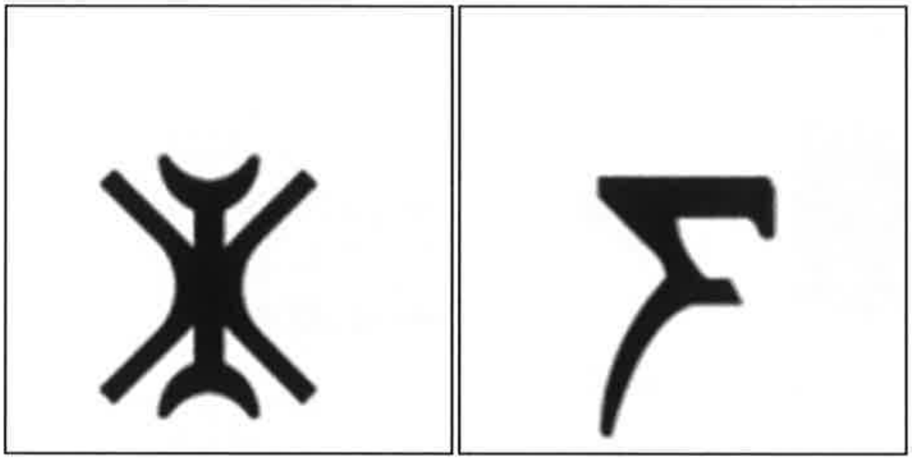

Fig. 4. Examples of klingon.
Note. The symbol of the number 8 (left) and the letter r in Klingon.

Fig. 4. The recall tests were modified in additional ways detailed in the Source Recognition Task section (4.1.4.1). The same power analysis was used for the primary and secondary memory components as with WMC in Experiment 1 and attentional control in Experiment 2, respectively. If one or both of primary and secondary memory benefit from viewing natural stimuli, then this could indicate that these memory components embedded within WMC measures also benefit by interacting with nature. However, if none of the memory processes benefit from nature, this would indicate that only attentional processes of WMC receive benefits from nature per the results of Experiment 2, where this outcome would be most consistent with the predictions from ART.

4.1. Materials and methods

4.1. 1. Participants

Ninety-four participants between the ages of 18–55 were recruited from the Montana State University Subject Pool for credit in an introductory psychology course or extra credit in higher-level psychology courses. The tasks were split into two different E-Prime Go programs linked separately on Qualtrics. The separate links and programs were created to prevent programs from crashing and limit the number of participants experiencing disappearing questions on the demographics portion of the experiment, as described in the ***Participants*** section (2.1.1) in Experiment 1. However, this resulted in six participants not completing the second half of the experiment. Also, one participant failed the attention check as described previously in the Method of Experiments 1 and 2, yielding a final number of 87 participants for analysis (*M* age = 20.68, *SD age* = 5.15, 32 male, 49 female, two other, and four invalid responses).

4.1. 2. Procedure

The procedure was the same as Experiments 1 and 2, but participants completed a total of three tasks, one each that either measured primary memory, secondary memory, or both of these two cognitive processes. Also, due to the limitations of the size of programming files, the source recognition task was always presented first in a separate link from the Klingon Span and the Continuous Paired Associates (CPA) which were presented in a random order.

4.1. 3. Nature and urban images

The same images were used as in Experiments 1 and 2.

4.1. 4. Primary memory and secondary memory tasks

4.1. 4.1. Source recognition task (primary and secondary memory). The recall from Shipstead et al. (2014) had to be modified due to the online medium. The ability to recall these icons is somewhat harder for these items compared to words and numbers. Originally, Shipstead et al. (2014)designated that items recalled within seven words or numbers presented or recalled were considered primary memory. In contrast, any items recalled beyond seven presented or recalled items were considered secondary memory, as described in Tulving and Colotla (1970). However, primary memory can only hold about four simple drawings (Luck & Vogel, 1997). Therefore, the presented and selected item cut-off was changed to four items, rather than seven items. Additionally, the ability for participants to draw these icons was impossible to program in E-Prime 3. Therefore, for each list, participants were presented with 12 icons to remember and then selected the studied items from a list of 60 icons presented on the screen. Therefore, participants selected the items that had been presented in the most recent list of 12 items with 48 "distractor" items from other lists. Although this makes the task more akin to a recognition test, distractor items from other tests were presented on the screen when it was time to respond, so it was more similar to how items were presented in the complex span tasks (e.g., see the final response screen as illustrated in Fig. 2A and B).

For the modified task, participants viewed a nature or urban image for 10 s and then were shown a list of 12 icons or Klingon letters one-at-a-time. Nature and urban images preceded five lists each, presented in a randomized order for 60 items to-be-remembered for each image type and a total for 120 items for all 10 tests. This task was designed to measure both primary memory and secondary memory by asking participants to select the 12 items in the reverse order from which they were presented. In this way, items toward the end of the 12-item list would be selected first and represent primary memory, whereas items presented at the beginning of the list would be selected last and represent secondary memory. For example, as shown in Fig. 5A, an icon of a taco was presented for 750 ms. If this were the last item presented (12th in the list) and then was the 1st to 4th item chosen as recognized from the presented list, then this would count as primary memory recognition. However, if the icon of the taco was the 5th to 12th item chosen as recognized from the list, then it was scored as a point for secondary memory recognition. Conversely, if the taco icon were presented 1st to 8th in the list, this item would always be scored as a secondary memory recognition because more than four additional items were presented after the taco icon. The range of possible primary memory scores is from 0 to 20 for each image type, and the range of possible secondary memory scores is from 0 to 60 for each image type. Participants had a total of 30 s to identify all 12 items in a given list.

4.1. 4.2. Klingon Span (primary memory). Participants completed two

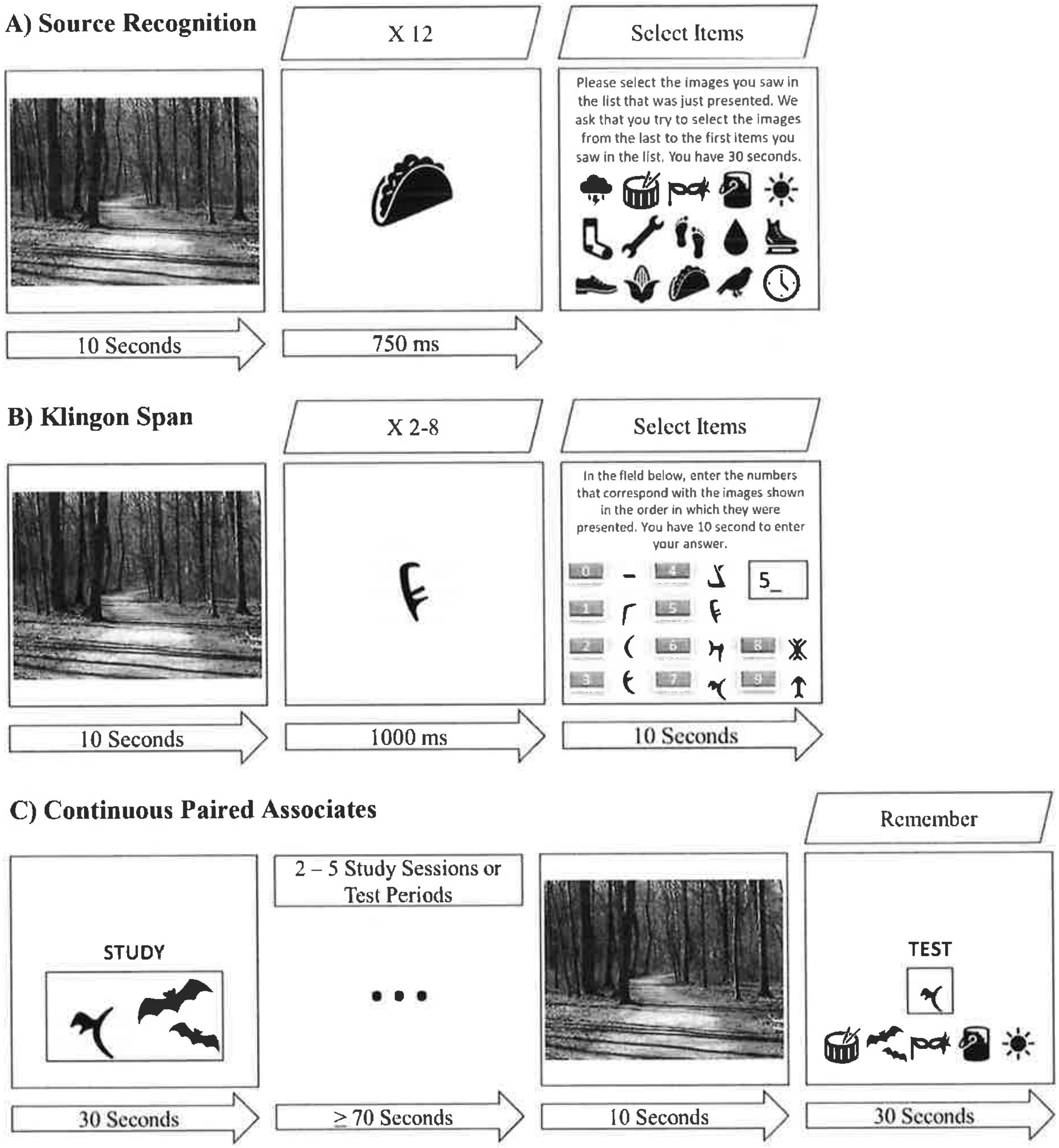

Fig. 5. Diagrams of nature and urban images presented before primary and secondary memory tasks.
Note. Although an image with a natural setting is shown in the figure, a nature or urban image was shown for 10 s. Also, although A in the final screen depiction only shows 15 items to illustrate the screen, 60 items were presented.

digit span tasks, termed Klingon Span, due to the change of numbers to Klingon symbols. One presented nature images for 10 s before each set of to-be-remembered Klingon symbols, whereas the other presented urban images. The order of these two tasks was randomized between subjects. For the Klingon span trials, a nature or urban image was presented for 10 s and then two Klingon numbers were presented one-at-a-time for 1 s each. After the set was presented, participants were shown all possible Klingon numbers and were given 10 s to select the presented Klingon numbers in the order they were shown. This procedure is depicted in Fig. 5B. If participants correctly recalled the presented Klingon numbers for two out of three trials, they moved to three more trials where the set size increased from two to three Klingon number presentations. This pattern continued until the set size of the Klingon numbers was eight symbols long for 22 nature and 22 urban trials, with the set size of eight having one extra trial due to the number of nature and urban images that were available. However, if the participant failed to recall the entire Klingon symbol set or recalled it out of order for more than one of the three trials for a given set size, the task ended. The dependent measure was the number of trials in which they could correctly recall the set in the correct order, ranging from 0 to 22. Although typical forward spans can be scored by taking the highest set size that a person can memorize, this is the scoring method that Shipstead et al. (2014) used, which loaded highly on a latent factor for primary memory.

Continuous Paired Associates (CPA; Secondary Memory). Participants were asked to study icon pairs one-at-a-time for 30 s each. Over the course of studying these pairs, participants were later tested on previously studied pairs. Before each test period, one of the nature or urban images was shown for 10 s. The test periods were always two-to-five study sessions or test periods after the first presentation of the pair, for a minimum of 70 s between study sessions and their corresponding testing periods to ensure the task measured secondary memory. Each test period lasted 30 s. In total, there were 26 pairs that were studied and later tested in the task. Of the 26 test periods, 13 were preceded by nature images, and the other 13 were preceded by urban images. These images were randomly presented. This task is depicted in Fig. 5C. The final dependent variable was the percentage of correctly identified pairs in the testing periods.

4.2. Results and discussion

Z-scores were computed within each task to compare performance across tasks after viewing a nature versus an urban image. Descriptive statistics for primary memory are reported in Table 3. Four outliers were identified, but the results did not change when the outliers were included, so all observations were kept for all following analyses. With the *z*-transformed scores, a Task x Image Type (nature vs. urban) ANOVA was conducted to analyze the effect of viewing images on the performance of these tasks. For primary memory, there was no main effect of Image Type [$F(1,86) = .051, p = .821, \eta_p^2 < .001, BF_{10} = .138$] and no interaction with Task [$F(1,86) < .001, p = .989, \eta_p^2 < .001, BF_{10} = .163$] indicating no difference in primary memory task performance after viewing nature images compared to viewing urban images. These results provide additional evidence consistent with our *specificity hypothesis* because nature selectively affected attentional control, but not primary memory.

The same analysis was conducted for secondary memory, for which descriptive statistics can be found in Table 4. Twenty-three observations were identified as outliers and changed the observable effects. When all observations are included, the analysis indicates a significant effect of Image Type [$F(1,86) = 4.668, p = .034, \eta_p^2 = .051, BF_{10} = .961$] such that performance on nature trials was .094 standard deviations greater than urban trials. There was no Task x Image Type interaction [$F(1,86) = .345, p = .559, \eta_p^2 = .004, BF_{10} = .674$], indicating that both tasks' performance was greater on nature trials. However, when outliers were removed in a pairwise method (15%), the main effect of Image Type became marginal [$F(1,73) = 3.552, p = .063, \eta_p^2 = .046, BF_{10} = .540$]. Given that our BF_{10} statistic was less than 1 for both analyses and excluding the outliers still allowed us to reach 80% power, the results suggest that secondary memory does not benefit from viewing natural stimuli and provide further consistent evidence with our *specificity hypothesis* because nature selectively benefits attentional control, but not primary memory or secondary memory. It seems that any benefits seen for WMC in prior studies may have been due to underlying benefits for the attentional control process, rather than either of the two memory components.

5. General Discussion

Our study examined nature's beneficial effect on WMC and its component processes. Results from Experiment 1 showed that WMC performance did not benefit from looking at natural images compared to urban images. However, results from Experiment 2 showed that attentional control did benefit from viewing nature images compared to urban images. These results provide evidence against our *sensitivity hypothesis*. If all WMC components benefited from nature, WMC would be the most sensitive to nature's benefits. However, results from our first two experiments showed that when the same natural stimuli were used to examine benefits across tasks, WMC showed no benefit, but attentional control did, supporting our *specificity hypothesis*. The benefits to WMC tasks likely need a stronger manipulation of nature because nature's benefits may be diminished due to little-to-no effects on primary memory and/or secondary memory when compared to the component processes of attentional control. Perhaps with greater interactions with natural stimuli, benefits could appear in WMC tasks.

Experiment 3 investigated the memory component processes of WMCand further supported our *specificity hypothesis*. More specifically, primary memory showed no benefits after viewing nature compared to urban images. Turning to secondary memory, although the main effect of Image Type was significant for secondary memory, our Bayesian analysis leaned toward evidence for the null hypothesis and was no longer significant without outliers. Therefore, we concluded that secondary memory did not benefit from viewing nature compared to urban images. This result further supported the *specificity hypothesis* because only one of WMC's three components – attentional control – received benefits from interacting with nature and not the two others. Taken together, the pattern of results observed across Experiments 2 and 3 – benefits of interacting with nature for attentional control, but not for primary or secondary memory, respectively – likely contributed to the null effect of nature we observed and reported in Experiment 1 while using measures of WMC.

Our results support ART's prediction that directed attention, in particular, benefits when viewing natural stimuli (Kaplan, 1995). Stevenson et al. (2018) came to the conclusion that working memory, cognitive flexibility, and attentional control domains may be sensitive to the benefits of nature. However, it is important to note that Stevenson et al. (2018) categorized primary memory tasks with WMC tasks for their *Working Memory* construct. Additionally, backward spans have more recently been shown to reflect working memory in children, but only primary memory for adults (St Clair-Thompson, 2010). In this light, it is difficult to determine whether the *Working Memory* benefits from interacting with nature reported by Stevenson et al. were due to primary memory, secondary memory, attentional control, or some combination of these three different processes. Our investigation based our task categorization for primary/secondary memory (Experiment 3) and attentional control (Experiment 2) on previous latent analyses and the latest psychometric perspectives on these constructs to independently measure any influence nature might have on these three cognitive processes of interest (as well as considering whether nature might benefit these component processes in combination with one another via complex span measures of WMC as reported in Experiment 1).

A strength of our investigation is that we were able to keep our nature manipulation constant. Given that Stevenson et al. (2018) conducted a meta-analysis, there was a significant variety in the protocol that could not completely be addressed in their meta-analysis, such as the methodology of the intervention and the extent (*see* Kaplan, 1995) to which participants were interacting with natural stimuli. For example, although some experiments were more immersive by having participants go on nature walks, others were virtual manipulations akin to our own. This study controlled the methodology and the extent to which nature and urban stimuli were viewed.

Table 3
Unstandardized descriptive statistics for raw scores of primary memory tasks.

Task	Cronbach's α	Image Type	N	Mean (*SD*)	95% CI	Standard Error	Min	Max	Skew	Kurtosis
Klingon Span	.918	***Nature***	87	4.621 (5.116)	±1.090	.548	0	18	.923	−.311
		Urban	87	4.552 (4.432)	±.945	.475	0	16	.617	−.877
Primary Memory Recognition	.762	***Nature***	87	4.725 (2.777)	. ± .592	.298	0	18	.460	−.153
		Urban	87	4.690 (2.759)	±.588	.296	0	18	.238	−.820

Note. The scores of the Klingon Span and Primary Memory Recognition tasks were significantly and positively correlated ($r = .22, p = .004$). CI = 95% Confidence Interval.

Table 4
Unstandardized descriptive statistics for raw scores of secondary memory tasks.

Task	Cronbach's α	Image Type	N	Mean (*SD*)	95% CI	Standard Error	Min	Max	Skew	Kurtosis
CPA	.938	***Nature***	87	.872 (.222)	±.047	.024	0	1	−2.437	5.321
		Urban	87	.856 (.224)	±.048	.024	0	1	−2.331	5.285
Secondary Memory Recognition	.884	***Nature***	87	37.747 (11.83)	±2.522	1.269	5	56	−.630	−.029
		Urban	87	36.368 (11.81)	±2.518	1.267	1	57	−.699	.496

Note. The scores of the Continuous Paired Associates (CPA) and Secondary Memory Recognition tasks were significantly and positively correlated ($r = .50, p < .001$).

Another strength of our studies is the confidence in measuring our construct of interest. In Stevenson et al.'s (2018) review, WMC tasks and primary memory tasks were significantly affected by nature under their *Working Memory* domain. As discussed in the Introduction (1), it is not clear which processes really benefited from nature manipulations. However, because our WMC tasks showed excellent reliability, correlated highly, and had means that were around the halfway point of the entire range of scores similar to Draheim et al. (2021), we have increased confidence in our measurement of WMC. Therefore, we can be more certain that nature does not benefit WMC as a whole, but benefits could be seen due to other components of WMC.

Stevenson et al. (2018) found unreliable effects for their grouping of attentional control tasks. This is likely because of issues of attentional control measures not always accounting for speed-accuracy tradeoffs and using difference scores (see Draheim et al., 2021). Our task chosen with these considerations in mind have previously loaded highly onto a latent construct of attentional control and, more importantly, in the present study had even greater internal consistency, greater correlations, and similar accuracy and deadline scores to Draheim et al. (2021), again increasing our confidence that our chosen tasks were accurately and reliably measuring attentional control. Therefore, we are confident that there are indeed beneficial effects for attentional control after interacting with nature, as reported in Experiment 2.

However, it is surprising that benefits were observed for the Flanker Deadline task but not the Antisaccade. One reason for this could be that most of the difficulty comes from needing to look away from the cue. However, those with smaller screens had worse performance than those with larger screens. Perhaps controlling for screen size accounted for equipment variance such as refresh rate or processing power that would contribute to measurement variance in the tasks that would make it harder to find an effect of our image manipulation. Further replication is needed for both tasks, but the overall main effect with a presumably weaker manipulation of nature gives us confidence that there is a beneficial effect for attentional control.

It is also somewhat surprising that we did not observe an effect of nature on primary memory, given that Ohly et al. (2016) and Stevenson et al. (2018) showed benefits for the forward digit and backward digit span tasks, which are both considered to be measures of primary memory. Although much more limited in terms of studies, secondary memory has previously shown to be sensitive to nature's benefit through a recognition task (Szolosi et al., 2014). It is possible that the modifications to the primary and secondary memory measures due to the online platform could have compromised our construct validity. Therefore, we conducted a confirmatory factor analysis, as shown in Appendix B. Our analysis showed that each task significantly loaded onto their predicted cognitive processes, and the two-factor model was a better fit than the one-factor model. Additionally, each task had moderate-to-high reliability. Therefore, our modifications of changing letters and numbers to icons and Klingon symbols to prevent cheating apparently did not alter our construct validity of primary memory and secondary memory. As mentioned in the Introduction, these previous benefits of nature observed in the forward and backward digit span tasks may reflect attentional control, which may be needed to avoid proactive interference after successive trials. Additionally, attentional control may have been needed for Szolosi et al.'s (2014) recognition task to avoid the distraction of the new images and to retrieve the ones they previously viewed. Again, we are confident that our tasks reflected the cognitive processes that we were interested in measuring, so previous benefits observed in similar tasks may have been primarily driven by benefits to attentional control due to tasks measuring more than the construct of interest.

On the other hand, a potential limitation is that our null effect for the WMC tasks in Experiment 1 may be due to limited interaction with natural stimuli, therefore diminishing the measurable effect because only the component of attentional control received an effect, as shown in Experiment 2. Previous research has shown benefits for other complex span tasks, such as the Operation Span task after a 50-min walk in nature (Bratman et al., 2015), but not after taking a 30-min walk in nature (Scott et al., 2023). Although our manipulation of nature may have been weaker than some nature manipulations in the literature, we feel confident that our image viewing was strong enough to examine nature's benefits to cognition because Szolosi et al.'s (2014) nature images resulted in recognition benefits after only 5 s of viewing and the urban images from Berman et al. (2008) did not show significantly greater performance in pre versus post testing for the backward digit span or the executive/attentional control portion of the ANT when viewing the images for 7 s each compared to their nature images. Therefore, the nature stimuli produce differences even when viewed for short durations and the urban images do not reliably affect performance in short duration.

However, a recent meta-analysis claims that simulated nature, such as nature images, does not reliably improve performance on attentional control as measured by the ANT (Johnson et al., 2021). One problem is that this task uses difference scores for reaction times, which may contribute to the instability of findings. The significant difference in attentional control performance between nature and urban trials in the Experiment 2 with improved task selection indicated that the intervention was successful. Therefore, according to the evidence for our *specificity hypothesis*, WMC may need a stronger manipulation of nature than what was given because it is diminished by the null effect of primary memory and secondary memory. To help researchers manage choices in experimental design when investigating environment and cognition, Watson et al. (2024) proposed a tetrahedral model. More specifically, Watson et al. suggested ongoing research on nature's influence on attention should be organized by four vertices of a Problem Pyramid - materials, outcomes, participants, and context - as originally inspired by Jenkins' (1979) work in the domain of memory. For example, with respect to outcomes, the current study held image materials constant to experimentally demonstrate a dissociation such that nature is more likely to benefit some measures (and underlying cognitive processes) than others. With regard to materials and the choice of whether to use outdoor settings or images for a manipulation, respectively, as complementary approaches, both more realistic, immersive and more controlled, laboratory studies are likely necessary to more thoroughly and completely investigate the empirical space and the potential impact of environment on cognition. More generally, Watson et al. noted that the overlap between the four methodological points of the tetrahedral framework demonstrates the importance of (and opportunity in) researchers considering statistical interactions to more fully address the complex relationship between nature and cognition.

Carrying this tetrahedral logic forward, although the present study demonstrated that some tasks/cognitive processes are more likely to receive benefits from interacting with nature than others, the materials used to manipulate nature and urban conditions would be a fruitful avenue for future research. Stronger manipulations could be longer durations, more fascinating images, more immersion in nature, and so forth. However, it is difficult to determine precisely why nature specifically benefits cognition apart from impacting attentional control. The characteristic we used to choose nature images was fascination, but this could be one of many characteristics of the nature images influencing attentional control. Specifically, in Appendix A, the nature and urban images are compared and differ on fascination, mystery, anxiety, likability, mindfulness, and resilience ratings. Future research could try to further disentangle what about these nature versus urban images, fascination or otherwise, may drive the benefit to attentional control by using the normative means and behavioral ratings provided in OSF.

However, even with stronger manipulations, beneficial effects of nature do not consistently emerge in other attentional control tasks. In Bratman et al.'s (2015), study participants took a nature walk for 50 min, therefore increasing the duration and immersion within nature, but they did not find a benefit for the attentional control portion of the ANT. However, another study had participants view nature images for 6 min, therefore providing less immersion and a shorter duration, but did find a benefit (Gamble et al., 2014). To better understand why these mixed results might be occurring even with stronger manipulations of nature, McDonnell and Strayer (2024) measured neural indicators of attentional control after a 40-min nature or urban walk. Greater error-related negativity (ERN) in regard to responses is likely a reliable indicator of executive function because it increases when participants are told to focus on accuracy over speed (Gehring et al., 1993). That is, when participants are focused on responding as fast as possible but not whether they are 100% accurate in the Flanker task, there are smaller ERNs because processing speed is more important. But when told to focus on accuracy, the magnitude of the ERN increases, placing more emphasis on attentional control. Specifically, when considering the speed-accuracy tradeoff, placing emphasis on accuracy means that participants must control their attention to inhibit the flanking distractors to overcome the interference with the target stimuli. Notably, the magnitude of ERN activity is also positively correlated with individual differences in WMC, and the likely role of attentional control in regulating neural activity following errors in behavior (Miller et al., 2012). Most importantly for the purposes of our discussion, although there were no behavioral benefits to any portion of the ANT, there was an enhanced ERN after the nature walk for the executive portion of the ANT (McDonnell & Strayer, 2024). Similar results have been shown in the Flanker task such that there is increased ERN amplitude during and after immersion in nature, but no behavioral effects even when camping (LoTemplio et al., 2020). Although increased attentional control does not always appear in behavioral measures after interacting with nature, it seems that there are still underlying neurological indicators of increased attentional control at different levels of analysis. The strength of the manipulation is, therefore, likely not as important as increasing the construct validity of measures by using neural/physiological markers of attentional control or by choosing attentional control tasks that have improved psychometric properties to find more consistent effects of nature's benefits to cognition.

An additional consideration of investigating nature's benefit to cognition is the participant's mental state. In keeping with the tetrahedral model (Watson et al., 2024) described above and the importance of considering the participants tested in one's experiments, our sample of college students is more likely than the general population to be cognitively fatigued (Kaplan, 1995; Tennessen & Cimprich, 1995; Versaevel, 2014). Even so, the fact that we did not cognitively fatigue our participants is a limitation. Research has been mixed on whether fatiguing participants is necessary (Stevenson et al., 2018). However, as mentioned in the Introduction, it is first important to identify which process actually benefit from nature so one can know what cognitive process needs to be fatigued. Future researchers investigating environment and cognition should consider the selection of fatiguing tasks as carefully as they choose their outcome tasks. Regardless, we are confident that fatigue alone did not determine our results because participants spent about 1 h on both the WMC tasks and the attentional control tasks and only a little over half an hour on the primary memory and secondary memory tasks. If participant fatigue alone did drive the effects seen in our study, we should have seen participants receive benefits from interacting with nature and urban images for both the WMC and attentional control tasks due to the similar amount of time spent on the tasks. However, as noted above, we only observed benefits of interacting with nature for attentional control (Experiment 2), but not for primary or secondary memory (Experiment 3), which likely contributed to the null effect of nature while using sensitive (but perhaps diluted) measures of WMC (Experiment 1) that are less specific to control by capturing all three cognitive processes. Even so, time spent on task may not be the best way to define fatigue from a processes perspective, because effort that can be fatigued has been defined differently across fields (Thomson & Oppenheimer, 2022). Therefore, although the level of fatigue may be important for finding an effect of nature on cognition, how and which process is measured by particular tasks or outcomes may be especially important for researchers to consider in their experimental designs.

6. Conclusion

These results highlight the need for additional work examining the benefit of nature to multi-component tasks and careful consideration of how to measure each cognitive process separately and when combined. Mixed results in past literature are most likely due to tasks measuring processes other than the presumed construct of interest. Therefore, testing cognitive processes when they are both separated into distinct tasks and united into single measures will help pinpoint which cognitive processes actually benefit from interacting with nature. The results of the present study, in conjunction with and consistent with ongoing empirical work on attention restoration theory, suggest attentional control is particularly likely to benefit from natural environments, which is consistent with our *specificity hypothesis*. Moving forward, future work considering the influence of environments on attention should consider using different behavioral measures per cognitive process using the latest psychometric perspectives and analytic techniques, such as latent variable analysis, to help select particular tasks, thereby increasing confidence in underlying construct validity.

Data availability

Data can be requested at https://osf.io/p2rzc/?view_only=b31fb7e310fa4214af640f9d13bb0c1d.

CRediT authorship contribution statement

Brooke Z. Charbonneau: Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jason M. Watson:** Writing – review & editing, Validation, Supervision, Software, Project administration, Methodology, Conceptualization. **Keith A. Hutchison:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization.

Appendix A

In addition to considering cognitive psychometric standards, our lab has focused on the stimuli used when investigating the potential benefits of nature. The pilot study briefly described here was to investigate how the same 40 nature and 40 urban images might differ with respect to psychological properties that may be related to cognitive and emotional benefits of nature through a behavioral norming study. We hypothesized that participants would rate nature as more fascinating (Kaplan, 1995), mysterious (Szolosi et al., 2014), and likable (Marois et al., 2021) than urban images. We also predicted that reports of anxiety (Ulrich et al., 1991) and mind wandering would be lower for nature images while reports of mindfulness and resilience would be higher, compared with urban images (Dzhambov et al., 2019).

A total of 405 participants (recruited from Amazon Mechanical Turk [N = 222], Montana State University [N = 90] and University of Colorado Denver [N = 93]) were asked to view 20 of 40 nature images (Szolosi et al., 2014) intermixed with 20 of 40 urban images (Berman et al., 2008). Those recruited from Amazon Mechanical Turk received monetary compensation for their time whereas students from the universities received course credit. After viewing each image for 5 s, participants were then asked to provide normative ratings for the nature and urban images on fascination using the *Shortened Perceived Restorativeness Scale* (Hartig et al., 1996), mystery (Szolosi et al., 2014), and likability on a Likert scale from 1 (A strong dislike) to 7 (A strong preference) as well as their self-reported state levels of anxiety using the six-item State/Trait Anxiety Inventory-State (Marteau & Bekker, 1992), mindfulness using the State Mindfulness Scale (Tanay & Bernstein, 2013), and resilience by reporting their agreement with the following statements: 1) "After viewing the previous image, I feel as if I could make it through a stressful event" and 2) "After viewing the previous image, I feel as if I could complete a challenging task" using a Likert scale from 1 (strongly disagree) to 5 (strongly agree). All ratings were presented in random order for each participant. Thought probes were also included right after seeing the image for 20% of trials of both nature and urban trials but before rating the images on the scales mentioned above to determine rates of mind wandering (Kane et al., 2017). For these thought probes, participants reported what they were just thinking about and were given the following options as responses of "The image," "Everyday stuff," "Current state of being," "Personal worries," "Daydreams," or "Other." The same attention checks were used in this normative study as the ones described in Experiment 1 (Maniaci & Rogge, 2014).

To determine if the rating significantly differed between nature and urban images, independent *t*-tests were conducted in an items-based analysis. Descriptive statistics can be found in Table B1. Participants rated nature images as more fascinating $t\,(78) = 4.45, p < 001, d = .994$, which is in line with ART (Kaplan, 1995). Also, in line with previous literature, nature images were more well-liked $t\,(78) = 5.29, p < .001, d = 1.18$, and more mysterious $t\,(78) = 4.98, p < .001, d = 1.11$ (Szolosi et al., 2014). Viewing nature compared to urban images also decreased anxiety $t\,(78) = -5.02, p < .001, d = -1.12$, and increased mindfulness $t\,(78) = 5.47, p < .001, d = 1.22$ and resilience $t\,(78) = 8.07, p < .001, d = 1.80$, respectively. However, there was no significant difference between the portion of mind wandering between the two image types $t\,(78) = -.442, p = .660, d = -.099$. These results both replicate and extend previous findings and suggest that more fascinating nature images tend to have positive effects on psychological experiences. Images and their mean normative ratings can be accessed on OSF (https://osf.io/p2rzc/?view_only=b31fb7e310fa4214af640f9d13bb0c1d).

Table A
Descriptive Statistics for Ratings of Nature and Urban Images for Each Variable

Type	Variable	n	Mean	SD	SE	95% C.I.
Nature	Anxiety	40	8.495	0.561	0.089	0.179
Urban	Anxiety	40	9.291	0.832	0.132	0.266
Nature	Fascination	40	3.145	0.190	0.030	0.061
Urban	Fascination	40	2.766	0.506	0.080	0.162
Nature	Likability	40	4.504	0.175	0.028	0.056
Urban	Likability	40	4.127	0.416	0.066	0.133
Nature	Mind Wandering	40	0.387	0.095	0.015	0.030
Urban	Mind Wandering	40	0.395	0.073	0.011	0.023
Nature	Mindfulness	40	3.263	0.068	0.011	0.022
Urban	Mindfulness	40	3.131	0.136	0.022	0.044
Nature	Mystery	40	5.045	0.177	0.028	0.057
Urban	Mystery	40	4.623	0.507	0.080	0.162
Nature	Resilience	40	3.124	0.086	0.014	0.027
Urban	Resilience	40	2.926	0.129	0.020	0.041

Appendix B

To ensure that the memory components were measuring separate constructs, a confirmatory factor analysis using JASP predicted two factors: primary memory and secondary memory. Following Shipstead et al. (2014), the scores of the Klingon span and items that were correctly recognized within four or fewer presentations/responses were loaded onto the primary memory factor and the scores of the CPA and all other correctly recognized items were loaded onto the secondary memory factor. Each latent variable was fixed to 1 for scaling to ensure no item was assumed to predict the factor more reliably than another. For the model to be considered a good fit, the chi square statistic should be non-significant, the CFI should be above .90, the RMSEA should be less than .05, and the SRMR should be below .10. The model was a relatively good fit for the data [$\chi 2\,(1) = .981$, p = .322, CFI = 1, RMSEA [90% CI] = 0 [.000, .282], SRMR = .019], with all significant factor loadings onto primary memory and secondary memory as depicted in Figure B. Importantly the two factor model fit better than the one-factor model [$\chi 2\,(2) = 2.179$, p = .336, CFI = .996, RMSEA [90% CI] = .032 [.000, .218], SRMR = .030], with all but primary memory significantly loading onto a general memory factor.

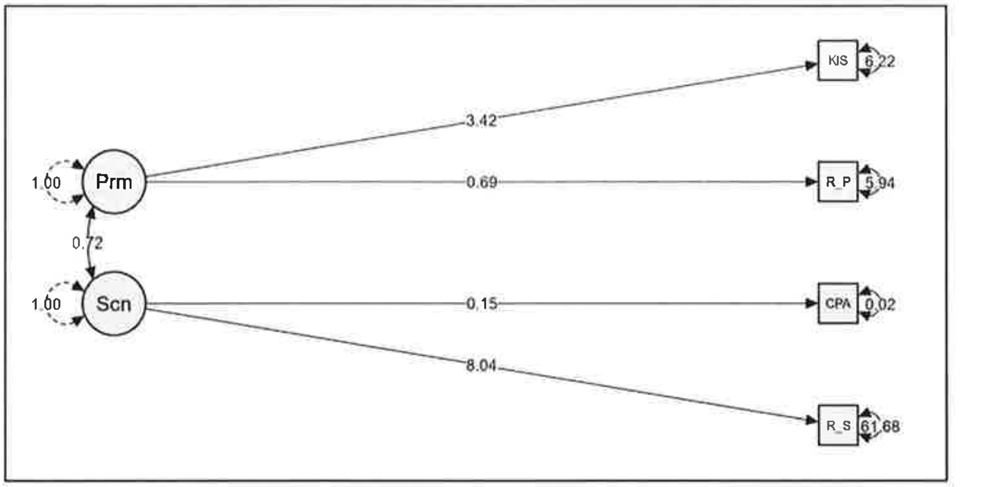

Fig. B. Model of Confirmatory Factor Analysis for Primary Memory and Secondary Memory.
Note. Prm = Primary Memory, Scn = Secondary Memory, KlS = Klingon Span, R_P = Primary Memory Recognition, CPA = Continuous Paired Associates, R_S = Secondary Memory Recognition.

References

Berman, M. G., Jonides, J., & Kaplan, S. (2008). The cognitive benefits of interacting with nature. *Psychological Science, 19*(12), 1207–1212. https://doi.org/10.1111/j.1467-9280.2008.02225.x

Bratman, G. N., Daily, G. C., Levy, B. J., & Gross, J. J. (2015). The benefits of nature experience: Improved affect and cognition. *Landscape and Urban Planning, 138*, 41–50. https://doi.org/10.1016/j.landurbplan.2015.02.005

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19*, 450–466.

Draheim, C., Tsukahara, J. S., Martin, J. D., Mashburn, C. A., & Engle, R. W. (2021). A toolbox approach to improving the measurement of attention control. *Journal of Experimental Psychology: General, 150*(2), 242–275. https://doi.org/10.1037/xge0000783

Dzhambov, A. M., Hartig, T., Tilov, B., Atanasova, V., Makakova, D. R., & Dimitrova, D. D. (2019). Residential greenspace is associated with mental health via intertwined capacity-building and capacity-restoring pathways. *Environmental Research, 178*, Article 108708. https://doi.org/10.1016/j.envres.2019.108708

Engle, R. W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science, 11*(1), 19–23. https://doi.org/10.1111/1467-8721.00160

Fernandes, M. A., Moscovitch, M., Ziegler, M., & Grady, C. (2005). Brain regions associated with successful and unsuccessful retrieval of verbal episodic memory as revealed by divided attention. *Neuropsychologia, 43*(8), 1115–1127. https://doi.org/10.1016/j.neuropsychologia.2004.11.026

Foster, J. L., Shipstead, Z., Harrison, T. L., Hicks, K. L., Redick, T. S., & Engle, R. W. (2015). Shortened complex span tasks can reliably measure working memory capacity. *Memory & Cognition, 43*(2), 226–236. https://doi.org/10.3758/s13421-014-0461-7

Gamble, K. R., Howard, J. H., Jr., & Howard, D. V. (2014). Not just scenery: Viewing nature pictures improves executive attention in older adults. *Experimental Aging Research, 40*(5), 513–530. https://doi.org/10.1080/0361073X.2014.956618

Gehring, W. J., Goss, B., Coles, M. G. H., Meyer, D. E., & Donchin, E. (1993). A neural system for error detection and compensation. *Psychological Science, 4*(6), 385–390. https://doi.org/10.1111/j.1467-9280.1993.tb00586.x

Gonzalez-Espinar, F. J., Ortells, J. J., Sanchez-Garcia, L., Montoro, P. R., & Hutchison, K. A. (2023). Exposure to natural environments consistently improves visuospatial working memory performance. *Journal of Environmental Psychology, 91*, Article 102138. https://doi.org/10.1016/j.jenvp.2023.102138

Hartig, T., Korpela, K. M., Evans, G. W., & Garling, T. (1996). *Validation of a Measure of perceived environmental restorativeness* (goteb. Psychol. Rep. 26.7). *Göteborg: Department of Psychology, Göteborg University.*

Hicks, K. L., Foster, J. L., & Engle, R. W. (2016). Measuring working memory capacity on the web with the online working memory lab (the OWL). *Journal of Applied Research in Memory and Cognition, 5*(4), 478–489. https://doi.org/10.1016/j.jarmac.2016.07.010

Hilbert, S., Nakagawa, T., Puci, P., Zech, A., & Buehner, M. (2015). The digit span backwards task. *European Journal of Psychological Assessment, 1*, 1–7. https://doi.org/10.1027/1015-5759/a000223

Hood, A. V., Hart, K. M., Marchak, F. M., & Hutchison, K. (2022). Patience is a virtue: Individual differences in cue-evoked pupil responses under temporal certainty. *Attention, Perception, & Psychophysics, 84*, 1286–1303. https://doi.org/10.3758/s13414-022-02482-7

Hood, A. V. B., & Hutchison, K. A. (2021). Providing goal reminders eliminates the relationship between working memory capacity and Stroop errors. *Attention, Perception, & Psychophysics, 83*(1), 85–96. https://doi.org/10.3758/s13414-020-02169-x

Hutchison, K. A. (2007). Attentional control and the relatedness proportion effect in semantic priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33*(4), 645–662. https://doi.org/10.1037/0278-7393.33.4.645

Ilkowska, M., & Engle, R. W. (2010). Working memory capacity and self-regulation. In R. H. Hoyle (Ed.), *Handbook of personality and self-regulation* (pp. 265–290). Wiley Blackwell. https://doi.org/10.1002/9781444318111.ch12.

Jacoby, L. L. (1991). A process dissociation framework: Separating automatic from intentional uses of memory. *Journal of Memory and Language, 30*(5), 513–541. https://doi.org/10.1016/0749-596X(91)90025-F

JASP Team. (2024). *JASP (version 0.18.3)[computer software].*

Jeffreys, H. (1961). *Theory of probability (3rd ed.).* Oxford University Press.

Jenkins, J. J. (1979). Four points to remember: A tetrahedral model of memory experiments. In *Levels of Processing in human memory*Hillsdale, NJ: Erlbaum: LS Cermak, FIM Craik, 429–46.

Johnson, J. A., Hansen, B. E., Funk, E. L., Elezovic, F. L., & Finley, J. C. A. (2021). Conceptual replication study and meta-analysis suggest simulated nature does not reliably restore pure executive attention measured by the attention network task. *Journal of Environmental Psychology, 78*, Article 101709. https://doi.org/10.1016/j.jenvp.2021.101709

Joye, Y., & Dewitte, S. (2018). Nature's broken path to restoration. A critical look at Attention Restoration Theory. *Journal of Environmental Psychology, 59*, 1–8. https://doi.org/10.1016/j.jenvp.2018.08.006

Kane, M. J., Gross, G. M., Chun, C. A., Smeekens, B. S., Meier, M. E., Silvia, P. J., & Kwapil, T. R. (2017). For whom the mind wanders, and when, varies across laboratory and daily-life settings. *Psychological Science, 28*(9), 1271–1289. https://doi.org/10.1177/0956797617706086

Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology, 15*(3), 169–182. https://doi.org/10.1016/0272-4944(95)90001-2

Kaplan, S., & Berman, M. G. (2010). Directed attention as a common resource for executive functioning and self-regulation. *Perspectives on Psychological Science, 5*(1), 43–57. https://doi.org/10.1177/1745691609356784

Kassambara, A. (2023). Ggpubr: 'ggplot 2' based publication ready plots. *R package version 0.6.0.* https://CRAN.R-project.org/package=ggpubr.

Kassambara, A. (2023). rstatix: Pipe-Friendly framework for basic statistical tests. *R package version 0.7.2.* https://CRAN.R-project.org/package=rstatix.

Lee, M. D., & Wagenmakers, E.-J. (2013). *Bayesian cognitive modeling: A practical course.* Cambridge University Press.

LoTemplio, S. B., Scott, E. E., McDonnell, A. S., Hopman, R. J., Castro, S. C., McNay, G. D., McKinney, T. L., Greenberg, K., Payne, B. R., & Strayer, D. L. (2020). Nature as a potential modulator of the error-related negativity: A registered report. *International Journal of Psychophysiology, 156*, 49–59. https://doi.org/10.1016/j.ijpsycho.2020.06.014

Luck, S., & Vogel, E. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390*, 279–281. https://doi.org/10.1038/36846

Maniaci, M. R., & Rogge, R. D. (2014). Caring about carelessness: Participant inattention and its effects on research. *Journal of Research in Personality, 48*, 61–83. https://doi.org/10.1016/j.jrp.2013.09.008

Marois, A., Charbonneau, B., Szolosi, A. M., & Watson, J. M. (2021). The differential impact of mystery in nature on attention: An oculometric study. *Frontiers in Psychology.* https://doi.org/10.3389/fpsyg.2021.759616

Marteau, T. M., & Bekker, H. (1992). The development of a six-item short-form of the state scale of the Spielberger State-Trait Anxiety Inventory (STAI). *British Journal of*

Clinical Psychology, 31(3), 301–306. https://doi.org/10.1111/j.2044-8260.1992.tb00997.x

McDonnell, A. S., & Strayer, D. L. (2024). Immersion in nature enhances neural indices of executive attention. *Scientific Reports, 14*, 1845. https://doi.org/10.1038/s41598-024-52205-1

Miller, A. E., Watson, J. M., & Strayer, D. L. (2012). Individual differences in working memory capacity predict action monitoring and the error-related negativity. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*(3), 757–763. https://doi.org/10.1037/a0026595

Ohly, H., White, M. P., Wheeler, B. W., Bethel, A., Ukoumunne, O. C., Nikolaou, V., & Garside, R. (2016). Attention restoration theory: A systematic review of the attention restoration potential of exposure to natural environments. *Journal of Toxicology and Environmental Health Part B: Critical Reviews, 19*(7), 305–343. https://doi.org/10.1080/10937404.2016.1196155

Persson, J., Welsh, K. M., Jonides, J., & Reuter-Lorenz, P. A. (2007). Cognitive fatigue of executive processes: Interaction between interference resolution tasks. *Neuropsychologia, 45*(7), 1571–1579. https://doi.org/10.1016/j.neuropsychologia.2006.12.007

Platt, J. R. (1964). Strong inference. *Science, 146*(3642), 347–353. http://www.jstor.org/stable/1714268.

Psychology Software Tools. (2022). *Bug: Slides with many Buttons at the end of a procedure incur large OnsetDelays*. PST Product Service & Support *[40361]* https://support.pstnet.com/hc/en-us/articles/7066213668247.

Psychology Software Tools, Inc. [E-Prime 3.0]. (2016). Retrieved from https://support.pstnet.com/.

Psychology Software Tools, Inc. [E-Prime Go]. (2020). Retrieved from https://support.pstnet.com/.

Qualtrics. [Qualtrics], (2005). Retrieved from https://www.qualtrics.com.

R Core Team. (2023). *R: a language and environment for statistical computing*. Vienna, Austria. Retrieved from https://www.R-project.org/.

Revelle, W. (2024). psych: Procedures for psychological, psychometric, and personality research. *Northwestern University, Evanston, Illinois. R package version 2.4.1*. https://CRAN.R-project.org/package=psych.

Schacter, D. L. (1996). *Searching for memory: The brain, the mind, and the past*. Basic books.

Scott, E. E., Crabtree, K. W., McDonnell, A. S., LoTemplio, S. B., McNay, G. D., & Strayer, D. L. (2023). Measuring affect and complex working memory in natural and urban environments. *Frontiers in Psychology, 14*, Article 1039334. https://doi.org/10.3389/fpsyg.2023.1039334

Shipstead, Z., Lindsey, D. R. B., Marshall, R. L., & Engle, R. W. (2014). The mechanisms of working memory capacity: Primary memory, secondary memory, and attention control. *Journal of Memory and Language, 72*(C), 116–141. https://doi.org/10.1016/j.jml.2014.01.004

St Clair-Thompson, H. L. (2010). Backwards digit recall: A measure of short-term memory or working memory? *European Journal of Cognitive Psychology, 22*(2), 286–296. https://doi.org/10.1080/09541440902771299

Stevenson, M. P., Schilhab, T., & Bentsen, P. (2018). Attention restoration theory II: A systematic review to clarify attention processes affected by exposure to natural environments. *Journal of Toxicology and Environmental Health Part B: Critical Reviews, 21*(4), 227–268. https://doi.org/10.1080/10937404.2018.1505571

Szolosi, A. M., Watson, J. M., & Ruddell, E. J. (2014). The benefits of mystery in nature on attention: Assessing the impacts of presentation duration. *Frontiers in Psychology, 5*, 1360. https://doi.org/10.3389/fpsyg.2014.01360

Tanay, G., & Bernstein, A. (2013). State Mindfulness Scale (SMS): Development and initial validation. *Psychological Assessment, 25*(4), 1286–1299. https://doi.org/10.1037/a0034044.

Tennessen, B., & Cimprich, B. (1995). Views to nature: Effects on attention. *Journal of Environmental Psychology, 15*, 77–85. https://doi.org/10.1016/0272-4944(95)90016-0

Thomson, K. S., & Oppenheimer, D. M. (2022). The "effort elephant" in the room: What is effort, anyway? *Perspectives on Psychological Science, 17*(6), 1633–1652. https://doi.org/10.1177/17456916211064896

Tulving, E., & Colotla, V. A. (1970). Free recall of trilingual lists. *Cognitive Psychology, 1*(1), 86–98. https://doi.org/10.1016/0010-0285(70)90006-X

Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology, 11*, 201–230. https://doi.org/10.1016/S0272-4944(05)80184-7

Unsworth, N., Fukuda, K., Awh, E., & Vogel, E. K. (2014). Working memory and fluid intelligence: Capacity, attention control, and secondary memory retrieval. *Cognitive Psychology, 71*, 1–26. https://doi.org/10.1016/j.cogpsych.2014.01.003

Versaevel, L. N. (2014). *Canadian post-secondary students, stress, and academic performance - a socio-ecological approach*. London: The University of Western Ontario. Ph.D. thesis.

Watson, J. M., Marois, A., & Szolosi, A. M. (2024). Environment and cognition: A tetrahedral model for studies investigating nature's influence on attention. In J. M. Watson, A. Marois, & A. Szolosi (Eds.), *[Manuscript in preparation to be published in a special issue on Environment and cognition at the Journal of cognitive psychology]*.